The Kitten LWK

A More Practical Lightweight Kernel

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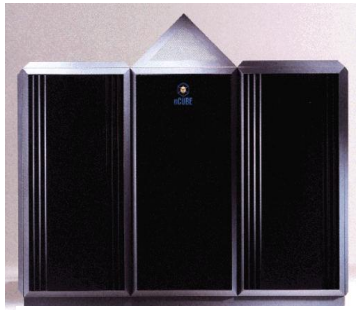
Sandia Has a Long History in MPP Architectures and System Software

I start at Sandia, late 2001

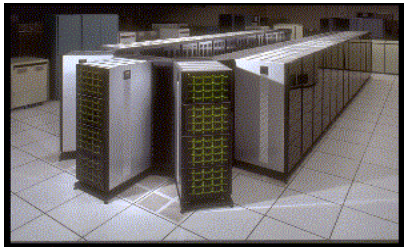
1990



nCUBE2

- Sandia's first large MPP
- Achieved Gflops performance on applications

1993



Paragon

- Tens of users
- First periods processing MPP
- World record performance
- Routine 3D simulations
- SUNMOS lightweight kernel

1997

ASCI Red

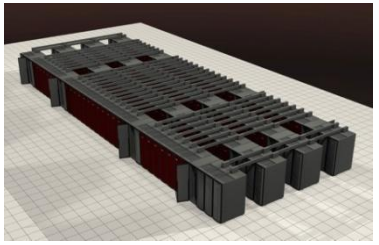
- Production MPP
- Hundreds of users
- Red & Black partitions
- Improved interconnect
- High-fidelity coupled 3-D physics
- Puma/Cougar lightweight kernel

1999

Cplant

- Commodity-based supercomputer
- Hundreds of users
- Enhanced simulation capacity
- Linux-based OS licensed for commercialization

2004



Red Storm

- 41 Tflops
- Custom interconnect
- Purpose built RAS
- Highly balanced and scalable
- Catamount lightweight kernel

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LWK Advantages

- **Improved scalability and performance**
  - Derived from taking full advantage of hardware and providing a more deterministic runtime environment
  - Primary motivator for use on capability systems
- **Simple resource management**
  - Deterministic virt->phys memory mapping, no demand paging
    - Simplifies network stack, no page pinning or page table walks
    - Enables single-copy intra-node MPI at user-level (SMARTMAP)
    - Enables transparent use of large pages, reduces TLB pressure
  - Simple task scheduling and affinity
- **Better platform for research**
  - Less complex code-base, slower moving target
  - Focus on what's important rather than working around problems

LWK is focused on "doing the right thing" for HPC on MPPs, being special-purpose provides freedom to innovate

LWK Disadvantages/Complaints

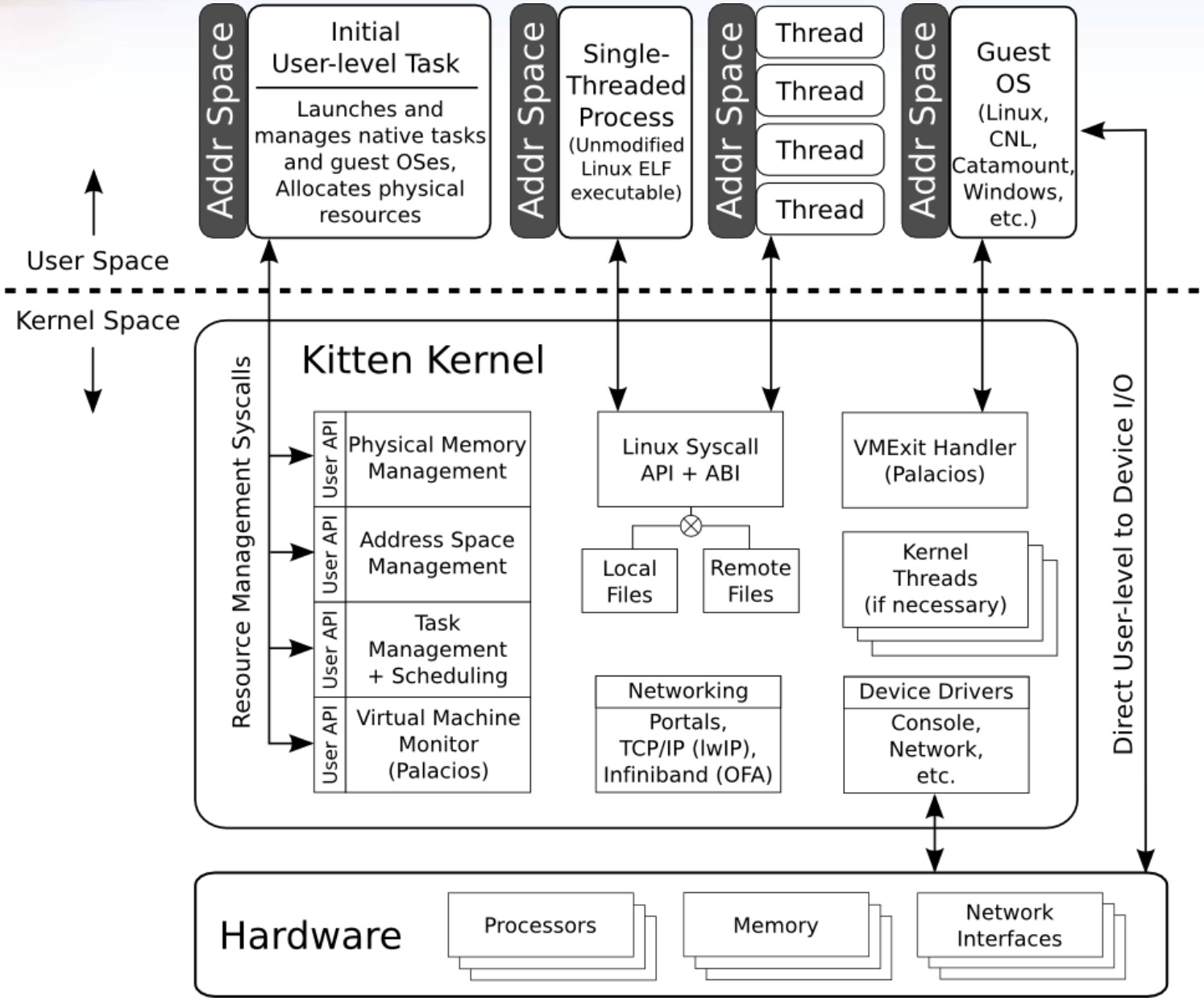
- **It's not Linux**
  - Everybody loves Linux! (myself included)
  - Is lightweight Linux still "Linux"?
- **It's missing feature X (threads, python, …)**
  - Can be mitigated by adding feature or through running guest OS
  - Users care about the environment, not implementation details
- **It's too much work to maintain**
  - All OSes will encounter issues on capability platforms
  - Low batting average getting HPC patches into Linux (.000?)
- **There's no community around it**
  - Existing LWKs are closed-source or closed-development
  - Bugs at scale are anything but shallow, not many eyeballs

Our position is LWK advantages will be required on future MPPs, trying to address or mitigate disadvantages with Kitten

Kitten: A More Practical LWK

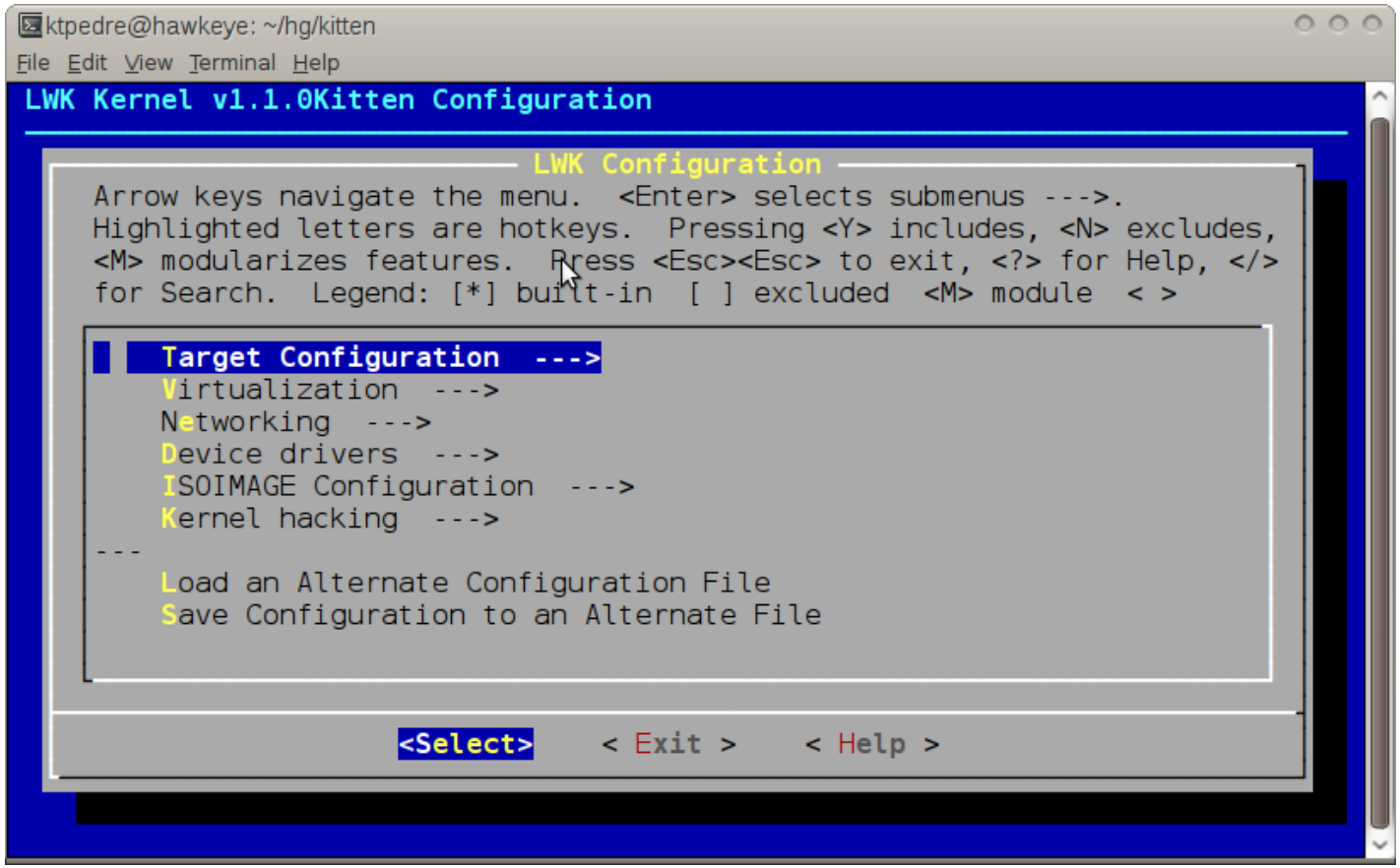
- **Open-source from start, open development**
  - Project website: http://software.sandia.gov/trac/kitten
  - Kernel is GPLv2, leverages code from Linux
  - User libraries are LGPL
- **Better match for user expectations**
  - Provides mostly Linux-compatible user environment, including threading
  - Supports unmodified compiler toolchains and resulting ELF executables
  - Leverages virtualization hardware to load full guest OSes on-the-fly (VMM capability provided by Palacios from V3VEE project, http://v3vee.org)
- **Better match vendor expectations**
  - Modern code-base with familiar Linux-like organization
  - Drop-in compatible with Linux (e.g., boots like CNL on Cray XT)
  - Infiniband support (currently in private tree)
  - Engaging with vendors and getting feedback
- **End-goal is deployment on future capability system**

Kitten Architecture



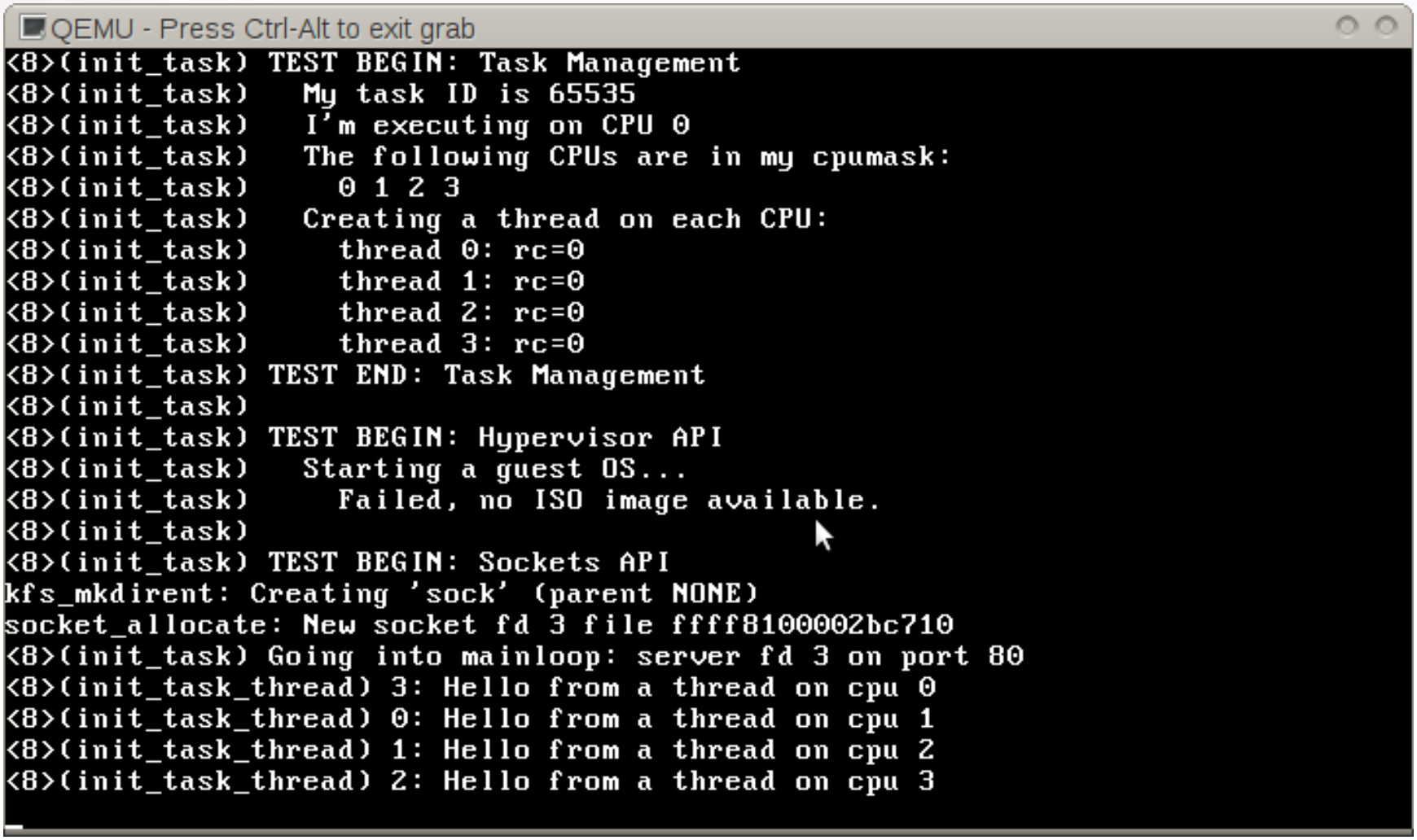
Improved Out-of-box Experience

```
make menuconfig; make isoimage
qemu-system-x86_64 -cdrom arch/x86_64/boot/image.iso -smp 4
```



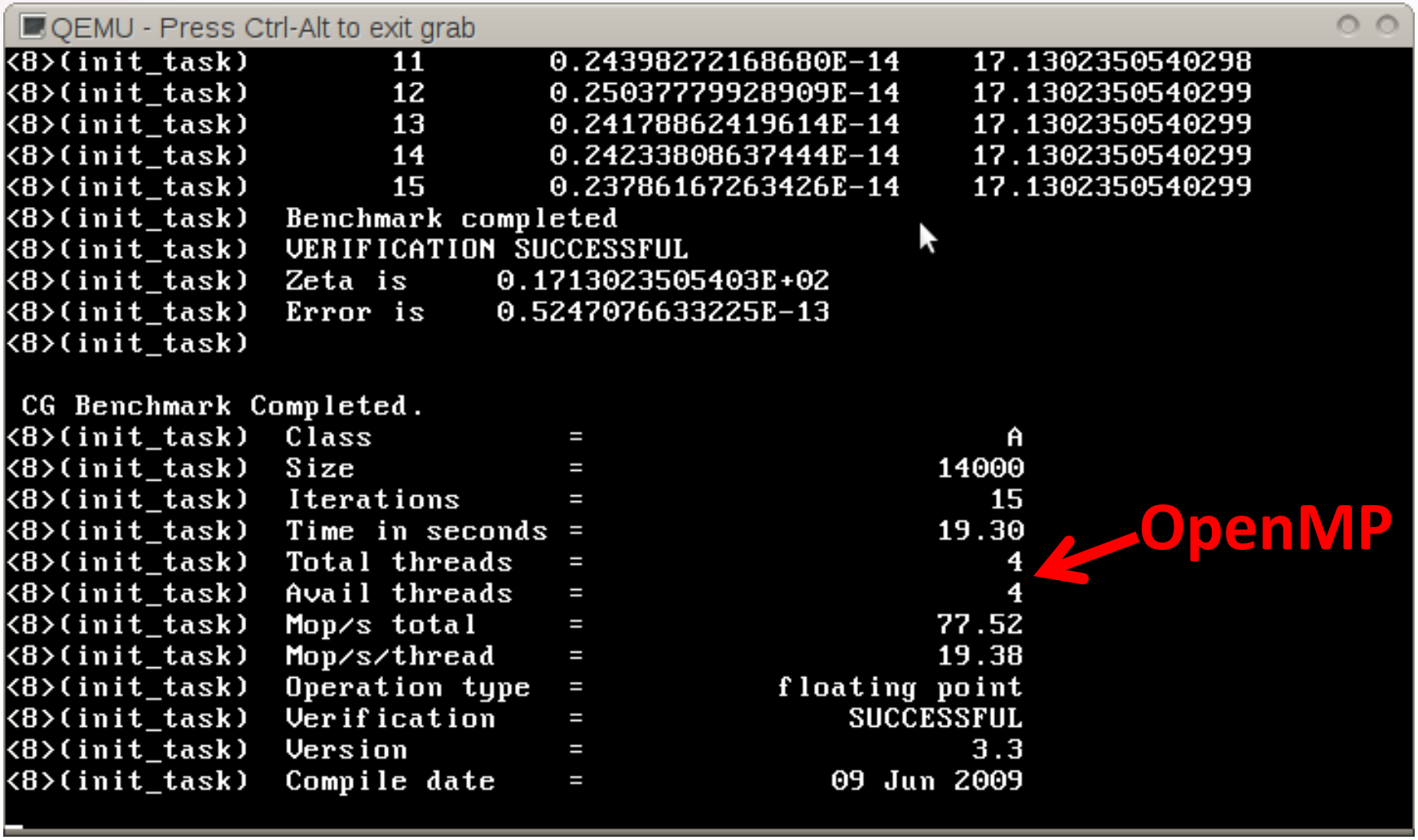
README includes directions for booting on PC hardware and Cray XT

Included “Hello World” Initial User Task



Source code: `kitten/user/hello_world/hello_world.c`

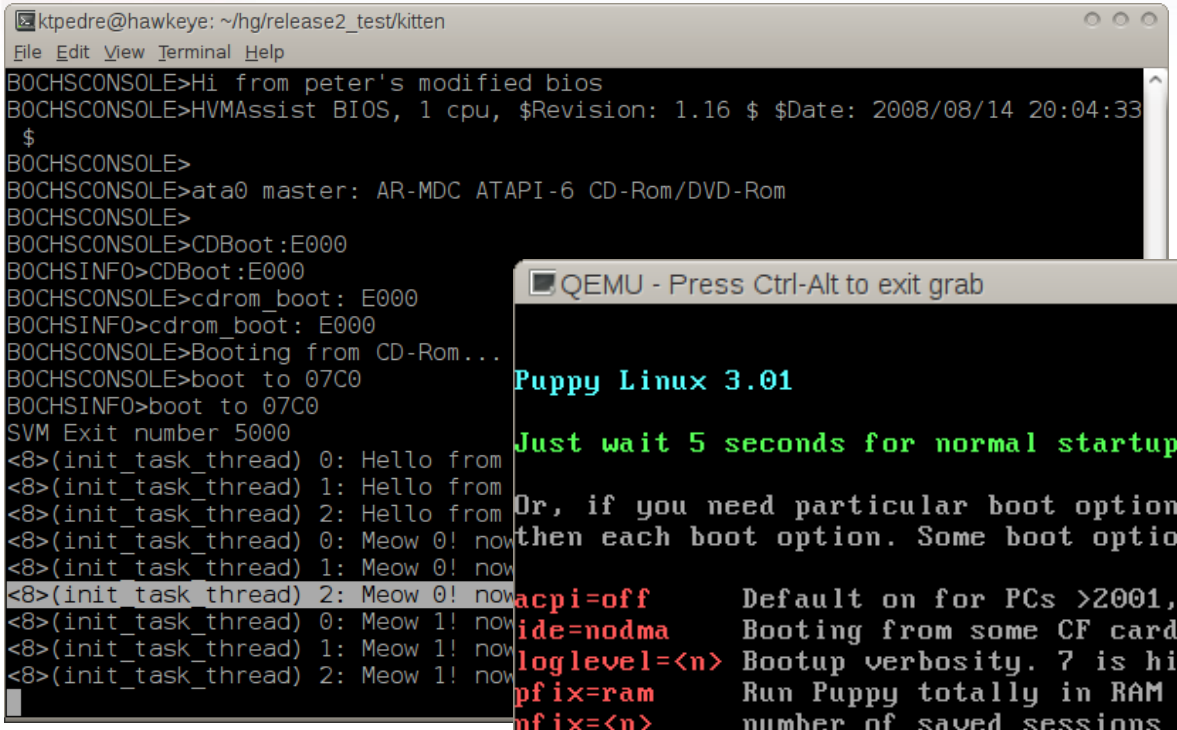
Running NPB CG.A as Initial Task (OpenMP, Fortran)

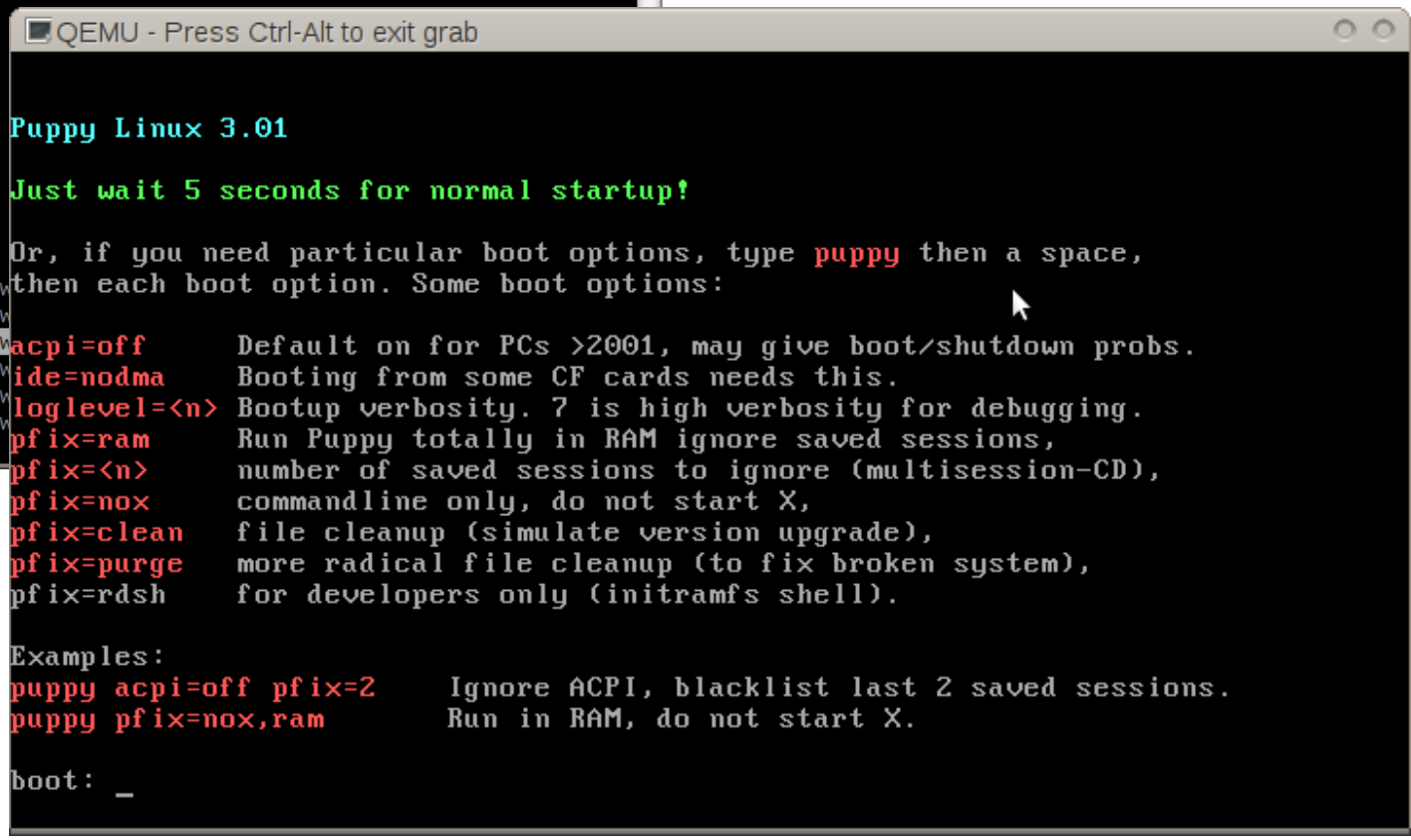


Environment:
"GFORTRAN_UNBUFFERED_ALL=y OMP_NUM_THREADS=4"
NPB print_results() modified to stop early for clarity

Running Puppy.ISO Linux as Guest OS

Kitten console on serial port, Puppy Linux outputs to VGA





puppy.iso is 95 MB image embedded in hello_world ELF executable, hello_world starts up then makes syscall to launch guest OS

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Motivations for Virtualization in HPC

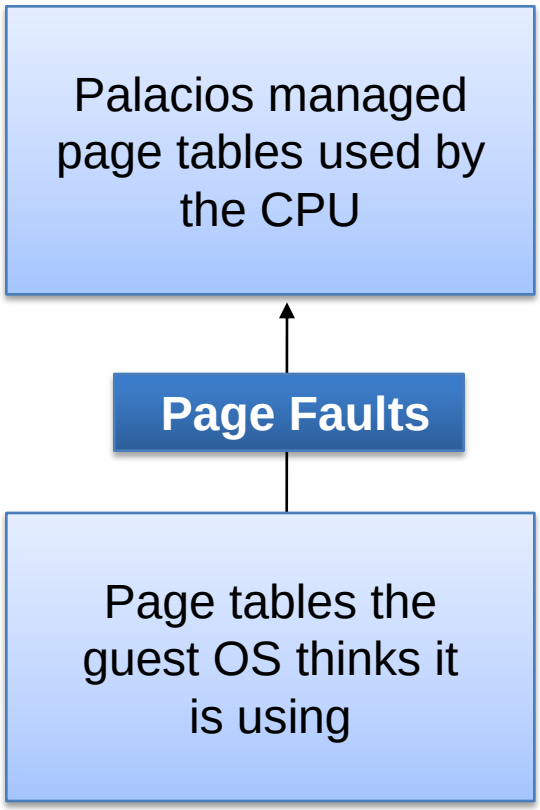
- **Provide full-featured OS functionality in LWK**
  - Custom tailor OS to application's needs (ConfigOS, JeOS)
  - Allow users to chose compute node OS on-the-fly
  - Potential to mix native LWK apps and guest OSes on same node
- **Dynamically assign compute node roles**
  - Currently service/compute ratio is fixed
  - Some jobs may benefit if allowed to specify a different balance
- **Runtime system replacement**
  - Capability runtimes often poor match for high-throughput serial
  - Runtime environment for guest OSes need not be the same
- **Improve resiliency**
  - Backdoor debug capabilities without special hardware
  - VM-based techniques for job checkpointing and migration

VM Overhead Investigation on Cray XT

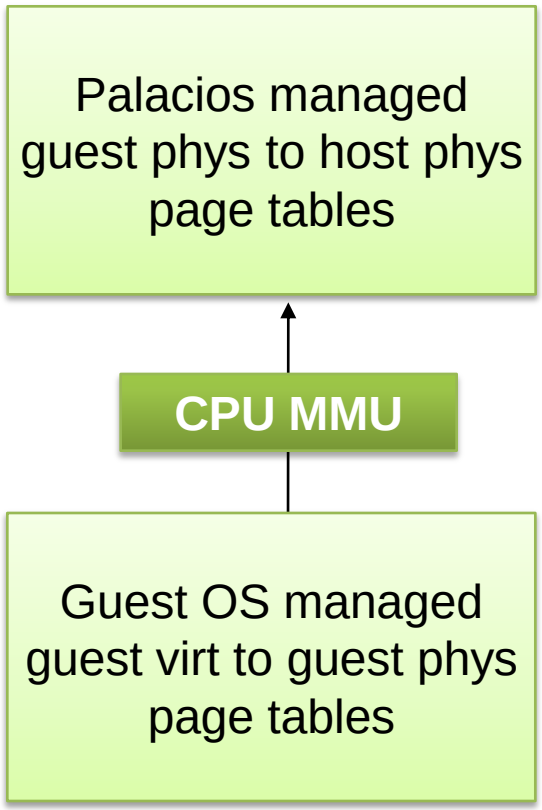
- **Two configurations:**
  - Native: Compute Node Linux (CNL) or Catamount on raw HW
  - Guest: Kitten+Palacios on raw HW, guest CNL or Catamount
- **For guest config, two paging schemes tested:**
  - Shadow: Software-based VMM control of guest page tables
  - Nested: Hardware-based control of guest page tables
- **Hardware:**
  - 48 node Cray XT4, 2.2 GHz AMD quad-cores (Budapest)
  - Planning larger-scale testing with more applications
- **Goal was to provide as thin a virtualization layer as possible to achieve best case VM performance**
  - SeaStar mapped directly into guest, driver para-virtualized
  - Guest allocated physically contiguous memory

Shadow vs. Nested Paging
No Clear Winner

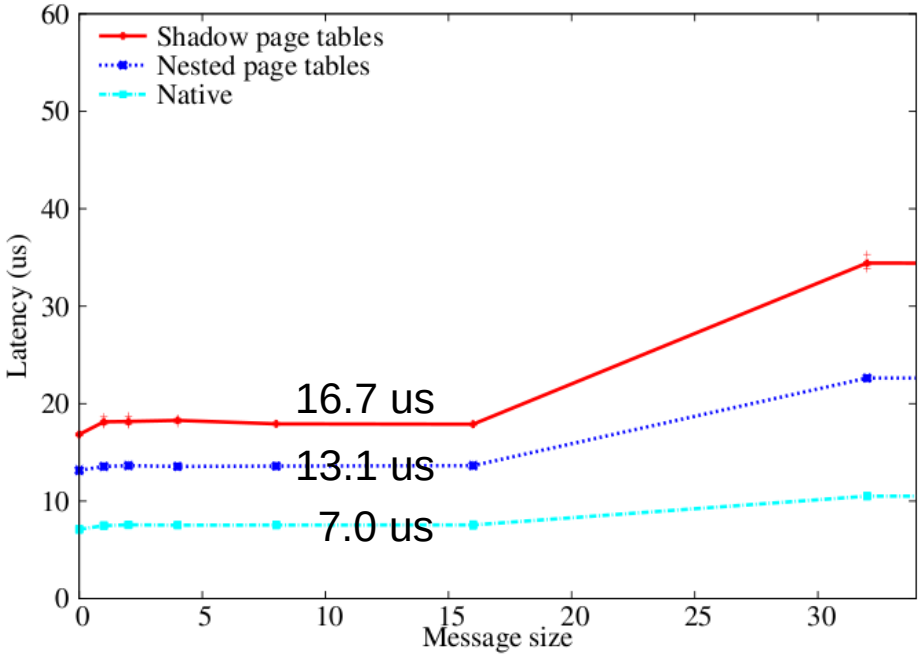
Shadow Paging
O(N) memory accesses per TLB miss



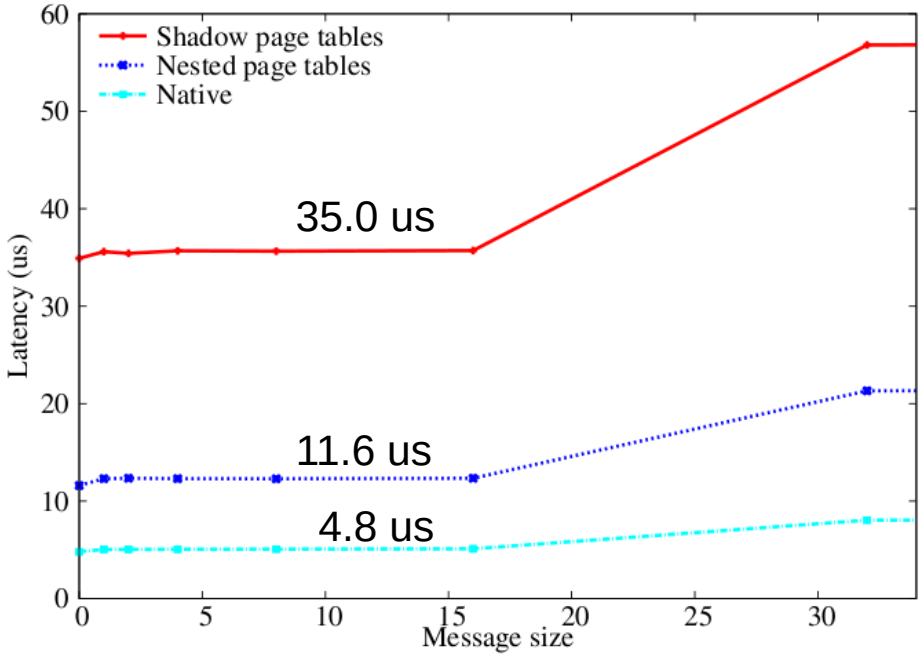
Nested Paging
O(N^2) memory accesses per TLB miss



IMB PingPong Latency: Nested Paging has Lowest Overhead



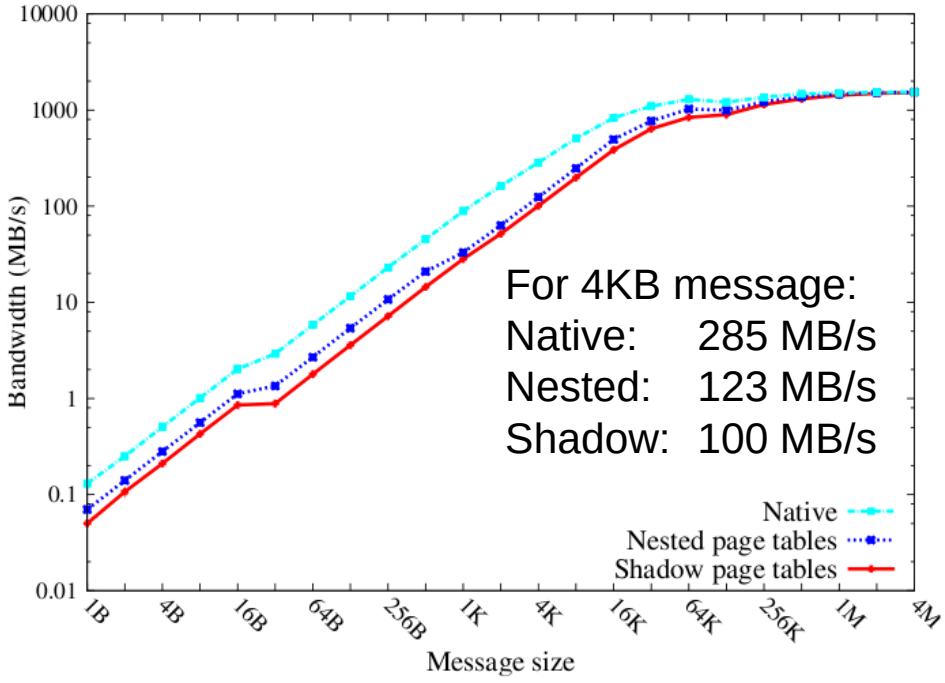
Compute Node Linux



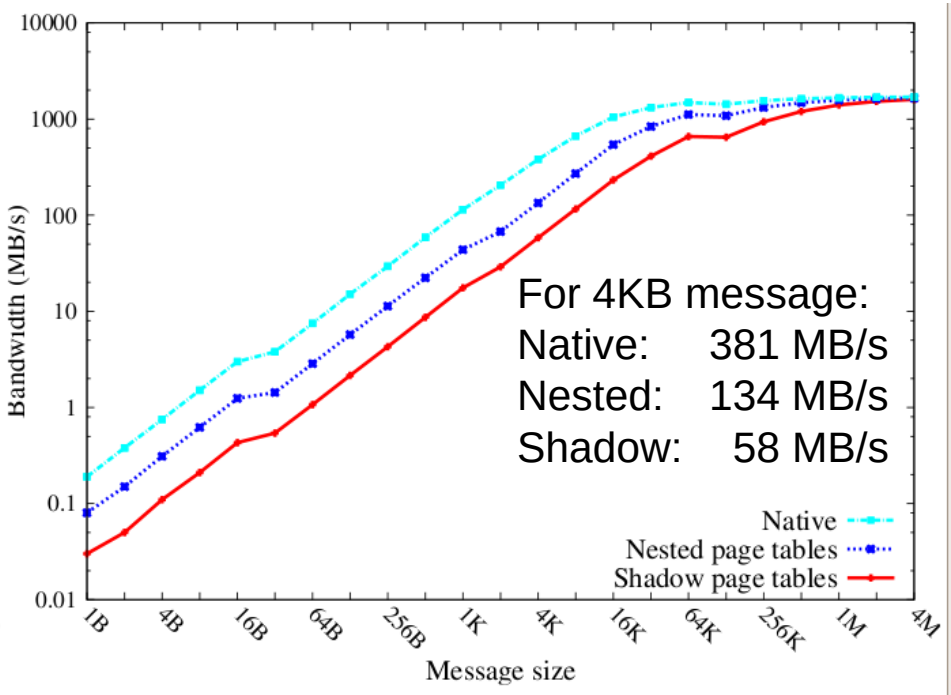
Catamount

Still investigating cause of poor performance of shadow paging on Catamount. Likely due to overhead/bug in emulating guest 2 MB pages for pass-through memory-mapped devices.

IMB PingPong Bandwidth: All Cases Converge to Same Peak Bandwidth



Compute Node Linux



Catamount

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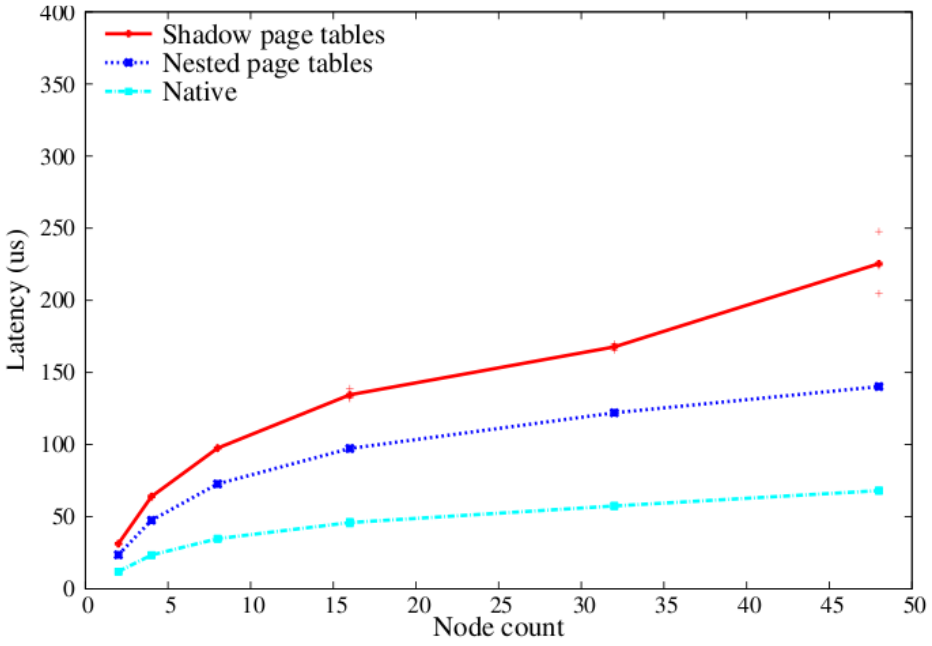
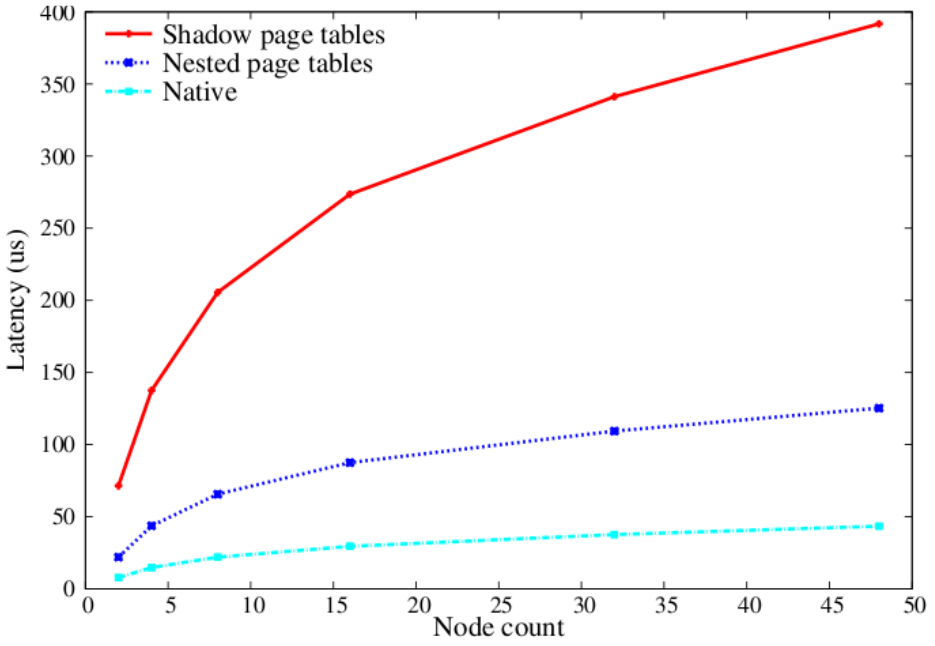
16-byte IMB Allreduce Scaling: Native and Nested Paging Scale Similarly



Compute Node Linux



Catamount

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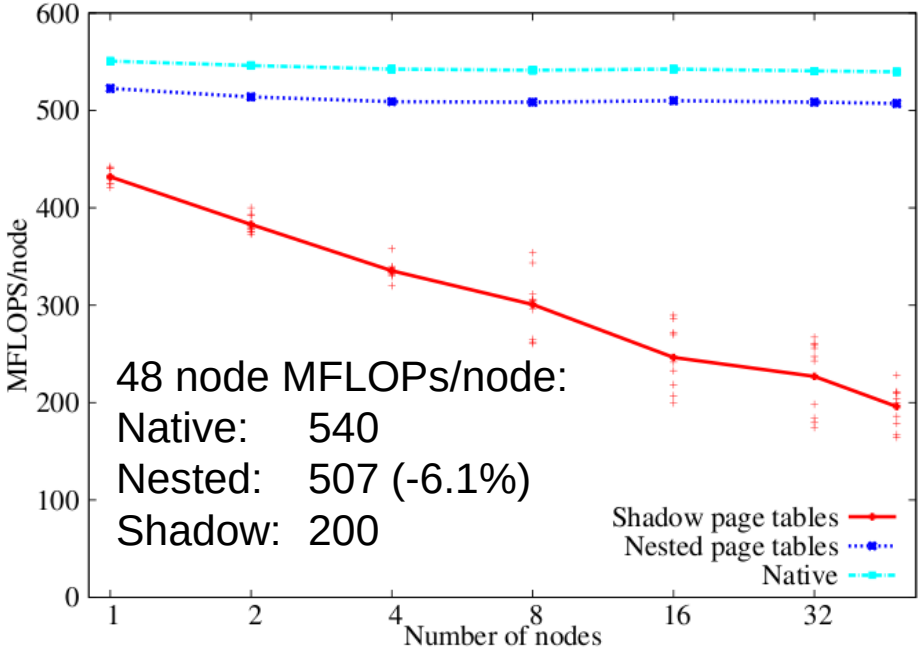
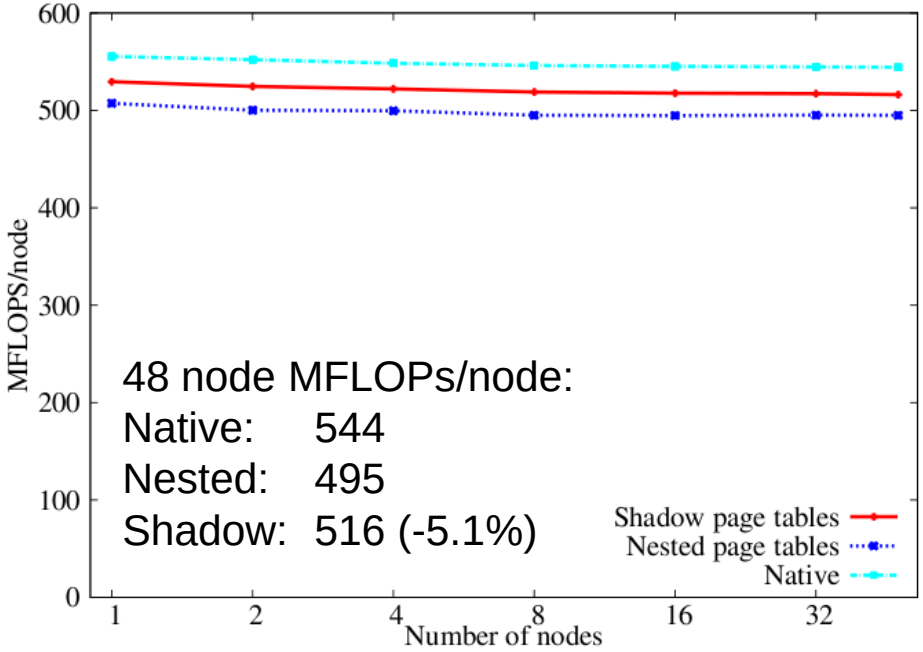
HPCCG Scaling
Sparse CG Solver, ~400 MB/node
5-6% Virtualization Overhead

Higher is Better



Compute Node Linux



Catamount

Poor performance of shadow paging on CNL due to context switching.
Could be avoided by adding page table caching to Palacios.

Catamount is essentially doing no context switching, benefiting shadow paging (2n vs. n^2 page table depth issue discussed earlier)

Sandia HPCCG miniapplication available from:
https://software.sandia.gov/mantevo/download.html

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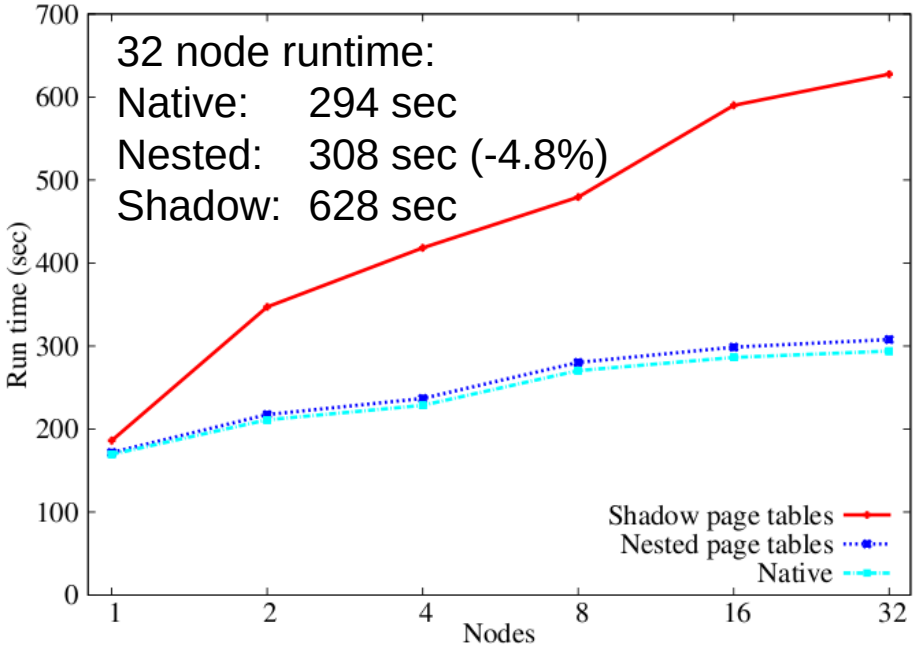
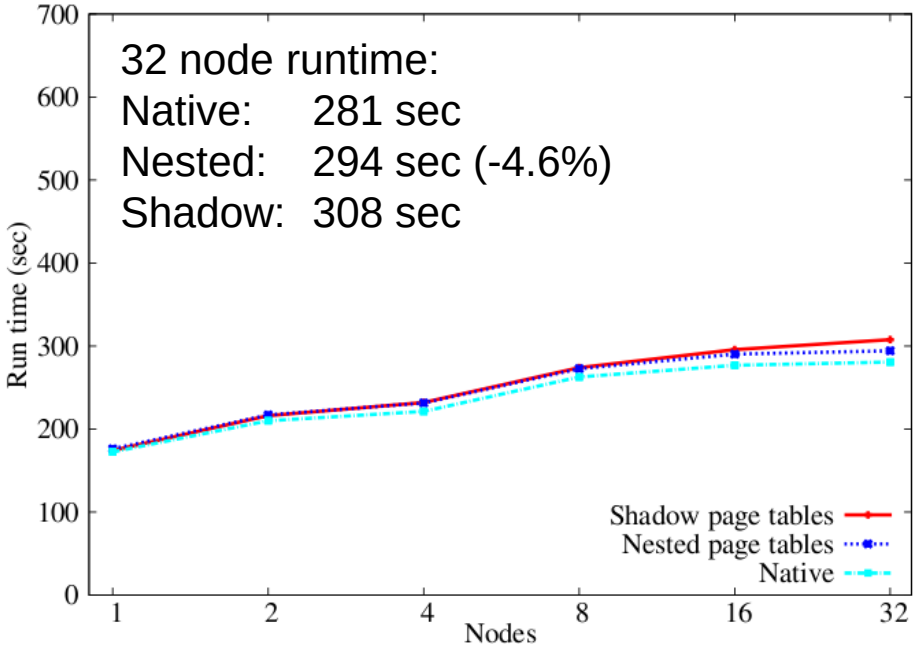
CTH Scaling
Shock Physics Application (Weak Scaling, No AMR)
< 5% Virtualization Overhead

Lower is Better



Compute Node Linux



Catamount

Poor performance of shadow paging on CNL due to context switching.
Could be avoided by adding page table caching to Palacios.

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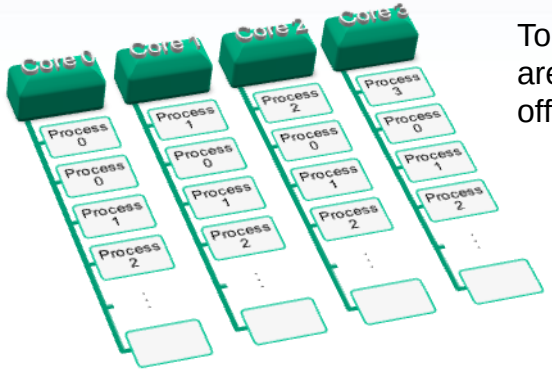
Future Virtualization Work

- **Support Accelerated Portals on Cray XT**
  - Eliminates interrupt overhead
  - Makes thin virtualization layer even thinner
- **Add support for SMP guests to Palacios**
- **Perform larger scale experiments**
  - Run on thousands of Cray XT nodes
  - Test more applications and more diverse guest Linux workloads
  - Evaluate newer CPUs (Shanghai, Istanbul, Nahalem)
- **Create user interface for loading guest OS/app**

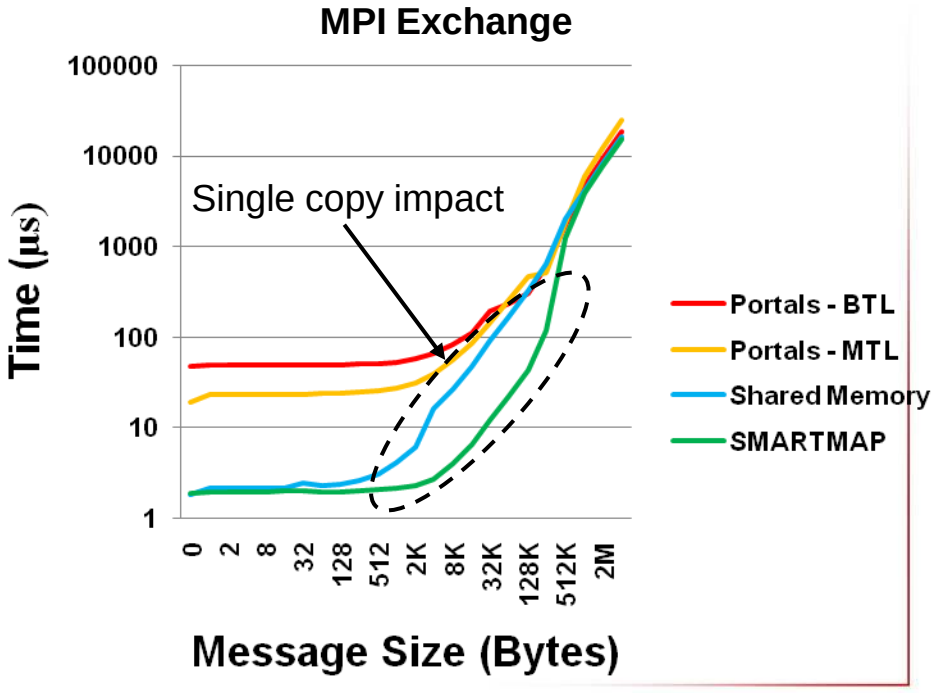
Kitten supports SMARTMAP

Simple Mapping of Address Region Tables for Multi-core Aware Programming

- Direct access shared memory between processes on a node
  - Access to “remote” data by flipping bits in the virtual address
- Each process still has a separate virtual address space
  - Everything is “private” and everything is “shared”
  - Processes can be threads
- Allows MPI to eliminate all extraneous memory-to-memory copies
  - Single-copy MPI messages
  - No extra copying for non-contiguous datatypes
  - In-place and threaded collective operations
- Not just for MPI
  - Emulate POSIX shared memory regions
  - One-sided PGAS operations
  - Can be used by applications directly
- Leverages lightweight kernel page table layout



Top-level page table slots are used to create a fixed-offset virtual address space



For more information see SC’08 paper on SMARTMAP

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Current Status

- **Current release (May 1, 2009)**
  - Available from http://software.sandia.gov/trac/kitten
  - Single node, multi-core, x86_64 only
  - Support for multi-threaded applications
    - Glibc NPTL POSIX threads
    - GCC OpenMP
    - Sandia Qthreads
  - Supports loading guest OSes via Palacios VMM
    - Boots guest Cray Linux Environment, Catamount, Kitten, and Puppy Linux
    - Supports AMD SVM only
    - Tested on PC hardware, Cray XT, and under Qemu
- **Development trees**
  - Support for unmodified OFA Infiniband stack (mthca and ml4x drivers)
  - Catamount user-level for multi-node testing (temporary scaffolding)
  - Exploring simplified job load mechanism via SLURM compatibility
  - Port of Kitten to NEC SX architecture

Conclusion

LDRD
LABORATORY DIRECTED RESEARCH & DEVELOPMENT

- **Kitten is a more practical LWK**
  - Fully open-source, open development
  - Better matches user, vendor, and researcher expectations
  - Straightforward out-of-box experience
  - Supports commodity hardware and (soon) Infiniband
- **Kitten provides a thin virtualization layer via Palacios**
  - Increases flexibility of LWK environment
  - Collaboration with separately funded V3VEE project (v3vee.org)
- **LWK enables novel optimizations for multi-core**
  - SMARTMAP
  - Exploring more opportunities

Acknowledgements

- **Kitten**
  - Michael Levenhagen (SNL)
  - Trammell Hudson (SNL)
  - Ron Brightwell (SNL)
- **SMARTMAP**
  - Ron Brightwell (SNL)
- **Palacios VMM**
  - Northwestern Univ: Peter Dinda and Jack Lange
  - U. of New Mexico: Patrick Bridges and Patrick Widener

Backup Slides

Lines of Code in Kitten and Palacios

Component	Lines of Code	
	sloccount .	wc *.c *.h *.s
Kitten		
Kitten Core (C)	17,995	29,540
Kitten x86_64 Arch Code (C+Assembly)	14,604	22,190
Misc. Contrib Code (Kbuild + lwIP)	27,973	39,593
Palacios Glue Module (C)	286	455
Total	60,858	91,778
Palacios		
Palacios Core (C+Assembly)	15,084	24,710
Palacios Virtual Devices (C)	8,708	13,406
XED Interface (C+Assembly)	4,320	7,712
Total	28,112	45,828
Grand Total	88,970	137,606

Kitten Leverages Linux

- **Repurposes basic functionality from Linux kernel**
  - Hardware bootstrap
  - Basic OS kernel primitives (locking, data structures, context switch, …)
  - Device driver API (supports unmodified OFA Infiniband stack)
  - User-level ABI and API (stack layout, thread-local storage, /sys, …)
- **Innovates in key areas**
  - Memory management
  - Network stack
  - Multi-core messaging optimizations (SMARTMAP)
  - Tick-less operation, OS work split into small pieces